SPECTRAL PHOTOMETRY OF EXTREME HELIUM STARS: ULTRAVIOLET FLUXES AND EFFECTIVE TEMPERATURES[1]

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ABSTRACT

We present ultraviolet flux distributions for the extremely helium-rich stars BD +10°2179, HD 124448, LSS 3378, BD -9°4395, LSE 78, HD 160641, LSIV -1°2, BD - 1°3438, HD 168476, MV Sgr, LS IV-14°109 (CD -35°11760), LSII +33°5 and BD +1°4381 (LSIV +2°13) obtained with the International Ultraviolet Explorer (IUE). Using broad-band photometry and a newly computed grid of line-blanketed model atmospheres, accurate angular diameters and total stellar fluxes have been determined. The resultant effective temperatures are in most cases in satisfactory agreement with those based on broad-band photometry and/or high-resolution spectroscopy in the visible. For two objects, LSII +33°5 and LSE 78, we find disagreement between the IUE-observations and broad-band photometry: the colors predict temperatures around 20,000 K, whereas the UV spectra indicate much lower photospheric temperatures of 14,000 - 15,000 K. Our new temperature scale for extreme helium stars extends to lower effective temperatures than that of Heber and Schönberner (1981) and covers the range from 8,500 to 32,000 K.

I. INTRODUCTION

This is the first in a series of papers concerning detailed examinations of a complete ensemble of extreme helium stars in order to elaborate important quantities such as effective temperatures, gravities and abundances in order to clarify their origin and evolutionary state. In this first publication we present the effective temperatures, based mainly on observations made with the IUE satellite. In forthcoming publications we shall give additional results of high-dispersion ground-based observations

Extreme helium stars have hydrogen depleted in their atmospheres by more than a factor of 10^3, and carbon is enriched by up to 1% (by number). Of the 13 known objects (we include MV Sgr, although it is classified as a R CrB star) only four have been analysed in detail (Heber and Schönberner 1981, and references cited therein). An empirical evolutionary sequence

$$\text{Log } T_{eff} = 3.7 + 0.25 \log g$$

connecting the R Cr B stars with the hotter extreme helium stars, can be derived from these analyses. This implies evolution with a constant ratio of L/M, or assuming the same mass of 0.7 M_o for all objects, with a constant luminosity ($\log L/L_o = 4.1 \pm 0.5$).[1]

A first attempt to establish a temperature scale for a representative ensemble of extreme helium stars was undertaken by Heber and Schönberner (1981). They determined effective temperatures by means of

[1]Hill et al. (1981) have derived T_{eff} = 25,500 K and log g = 4 for BD +13°3224, an extreme helium star with an anomalously high hydrogen abundance (n_H = 0.01). Consequently this object does not fall on the evolutionary track given by the above equation, but may be the prototype of a different class of objects.

colors, which were calculated for a grid of model atmospheres with appropriate ranges of temperature, gravity and composition (see for details Heber and Schönberner, 1981). These temperature determinations, however, suffered from: i.) at least partially inaccurate photometry, ii.) influences of the gravity on colors, and iii.) line blocking by lines other than helium, which becomes increasingly important for cooler stars and leads to wrong positions in the theoretical two-color diagram. Therefore, these temperatures are dependent on the model atmospheres used.

Ultraviolet observations offer a better prospect of success because the UV flux distribution is very temperature sensitive for B-type stars. Furthermore, the reddening can be estimated <u>model independently</u> by means of the 2200 Å feature. Therefore, we have combined UV fluxes measured by the IUE satellite with ground based photometry (UBV and infrared) in order to evaluate the total stellar fluxes together with angular diameters, and hence effective temperatures. A temperature scale established in this way is more nearly <u>model independent</u> and thus to be preferred. A preliminary report of this work has already been presented elsewhere (Schönberner *et al.*, 1982).

II. OBSERVATIONS AND REDUCTIONS

Low dispersion spectra of the known extreme helium stars have been obtained with the IUE satellite over the last four years. Spectra were obtained with the Short Wavelength Prime (SWP) and Long Wavelength Redundant (LWR) cameras. SWP spectra obtained between 14 June 1978 and 6 August 1979 were corrected for Intensity Transfer Function (ITF) errors using the 3-agency 4th file method (Cassatella *et al.* 1980). Most images were collected by the authors themselves. The rest were obtained from the National Space Science

Data Center (Warren 1982). All images were calibrated according to the recommendation of Bohlin and Holm (1980).

Images used in this analysis are presented in Table 1. Because our targets are quite distant, many of them show considerable reddening (Heber and Schönberner, 1981), and because of the faintness of these objects it was impossible to obtain well exposed spectrograms around 2200 Å for all of them. In these cases any correction for interstellar reddening is quite uncertain. We used the empirical formula of Seaton (1979), and the absence of the 2200 Å feature was used as a criterion for no reddening. For some objects two images were at our disposal, and in these cases we superimposed them in order to improve the S/N-ratio around the 2200 Å region. For hotter stars ($T_{eff} \gtrsim 14,000$ K), we were able to derive the color excess within $\pm$ 0.03 mag. For cooler stars with large line blocking, and for those with underexposed images around 2200 Å, we have to admit a larger error for the color excess (up to 0.1 mag). The color excesses are also given in Table 1 and compared with those of Heber and Schönberner (1981). For the hotter stars the agreement is excellent, but larger discrepancies show up for cooler objects. This is caused not only by the above mentioned observational uncertainty, but also by the neglect of metallic line blocking in the Heber-Schönberner computations, which gives an improper placement of the models in the color-color diagram. Our new results have the advantage of being nearly model independent and are therefore preferred throughout this work. The changes caused by different extinction laws are minor and cannot account for the differences in Table 1.

All spectrograms (corrected for interstellar reddening) are shown in Fig. 1, where they are arranged in the order of decreasing effective temperature. Very noisy parts are represented by averages or by least-squares fits to the

data points. The strong absorption features are typical for giants (see IUE-Spectral Atlas, Wu et al., 1981). Remarkable, however, is the very strong C II resonance absorption (λ = 1335 Å) in the intermediate temperature range, which is, of course, a result of the high carbon abundance ($n_C \sim 1\%$ by number). The same holds for the C IV resonance absorption (λ = 1550 Å) for the hotter objects. This line is still clearly visible in LSE 78, which has a temperature of about 14,000 K. High-resolution spectrograms of the three hottest stars, BD +10°2179, BD -9°4395 and HD 160641, reveal its origin to be an expanding envelope (Hamann et al., 1982). This is probably also true for the cooler objects, although an interstellar contribution might be possible. The cooler models (beginning with LSII +33°5 at ~ 15,000 K), show clearly the CI-absorption edge at λ = 1445 Å. In general, the high carbon opacity (C I and C II) is responsible for the far UV depression up to 20,000 K (see Fig. 2). At this resolution (~ 6 Å) none of the strong resonance lines appear to have emission components or are blueshifted in a way which is typical for high mass-loss rates. The calculation of mass loss in the three hottest extreme helium stars is treated in detail in the above quoted paper of Hamann et al., (1982).

III. MODEL ATMOSPHERES

Plane-parallel, static LTE atmospheres are adopted. Schönberner and Wolf (1974) and Schönberner (1975) have described the computational methods in some detail. Adopted continuous opacity sources include H I, H^-, He I, He II, He^-, C I, C II, C III, N I, N II, N III, O I, Mg I, Mg II, Al I, Si I, Si II, Ca II, and electron and Rayleigh scattering for H, He, C, N, O. Continuous opacities due to O I through to Ca II affect only the lower-temperature models

and have been adopted from Kurucz (1970). The carbon and nitrogen opacity is taken from Peach (1980) and includes the contributions of excited levels. This is important for cool models where the helium opacity is low. For helium, the recent photoionization cross sections of Jacobs (1974) were preferred. We included also the opacity of about 800 ionic line transitions in the UV, together with important helium lines in the visible (Heber and Schönberner, 1981) in order to account for line blanketing effects, at least partially. These 800 transitions involve about 400 spectral lines which are represented by nearly 2000 frequency points. Clearly, we have to admit that our treatment of line blocking is far from being sufficient when compared with the observations. We have to keep this in mind later when we wish to derive effective temperatures from the total emergent flux.

We computed theoretical flux distributions for a grid covering 9,000 K $< T_{eff} <$ 35,000 K and $1.0 < \log g < 3.5$. For all stars, the uniform chemical composition $n_H = 0$, $n_{He} = 0.99$, $n_C = 0.01$ (by number) is adopted, the other chemical elements being assumed to be solar with respect to the total mass ($\log\Sigma\ \mu_i n_i = 12.15$). Experience with the analysis of ground-based observations (e.g., Walker and Schönberner, 1981) shows that these abundances give generally good agreement with observation. The same grid has also recently been used in a fine analysis of BD+10^{o}2179 (Heber 1983).

IV. EFFECTIVE TEMPERATURES

We supplemented our IUE-spectrograms with broad-band photometry in order to get a wide spectral coverage of the stellar fluxes up to 3.6 μ. Details of this photometric study shall be presented in a forthcoming paper (Drilling et al., 1983). We converted the (corrected) magnitudes into fluxes according

to the recommendations of Hayes (1979) and of Wamsteker (1981). In passing we note that only one object, MV Sgr, has an IR-excess (Feast and Glass, 1973).

We determined the effective temperatures by the direct method, i.e., we applied the Stefan-Boltzmann law to the total emergent flux. For a description and excellent discussion of this method we refer to the two very recent publications of Böhm-Vitense (1981) and Underhill (1982). We had to consider, however, that our models do not describe the UV very well because of the missing line opacities mentioned in Sec. 3. We also remind the reader that the color excess is not well known in all cases (Sec. 2). We therefore simplified the procedure in the following way: first we fit the observed visual and infrared fluxes with a reasonable starting model, which in turn provided us with the angular diameter. The unobserved parts of the stellar flux were then, as usual, supplied by this model. The observed spectrum shortward of λ = 1240 Å was not used because of the effects of interstellar L_{α}-absorption and/or -geocoronal emission. Normally, one iterates until the model temperature and that given by the Stefan-Boltzmann law agree reasonably well. We cannot proceed in this way because our models are not fully blanketed. Instead, our criterion for the acceptance of a final model is as follows: the model flux must match the observed flux longward of 3000 Å for cool objects ($T_{eff} \lesssim$ 15,000 K) and longward of 2000 Å for the hotter ones. The difference between the temperature of the final model and that resulting from the Stefan-Boltzmann law turned out to be between 500 and 1000 K and can be attributed to line blocking in the (observable) UV.

The results are collected in Table 2 where we give also the effective temperature of the model that was used to derive the angular diameter and total flux. The errors are estimated from the uncertainties of Θ^2 (~10%) and the color excess and are, of course, larger for highly reddened and/or cool

objects. Table 2 also gives the quantity R which measures the UV flux gradient and is defined by

$$R = \int_{1240}^{1945} F(\lambda)\, d\lambda \Big/ \int_{1945}^{3120} F(\lambda)\, d\lambda \ ,$$

i.e., essentially the ratio between the integrated fluxes of the two cameras. We used that quantity quite successfully in a recent study of the effective temperatures of O-type subdwarfs (Schönberner and Drilling, 1983b). It is insensitive to the color excess because the flux depression in the SWP band caused by interstellar absorption is nearly compensated for by the $\lambda = 2200$ Å bump, which influences only the LWR region. We can therefore get fairly accurate values of R even if the color excess is poorly known. For instance, $E(B-V) = 0.1$ mag corresponds to $\Delta R \approx 0.05$. Thus the main source of error comes from the observational noise in badly underexposed images. In this case, the errors can be as large as 50%. For well exposed spectrograms, R is accurate within a few percent.

Because the UV flux gradient is very temperature sensitive in the temperature range considered here, the quantity R is well correlated with effective temperature. This is shown in Fig. 2 for the objects listed in Table 2. Within the errors, we have a well defined correlation, indicating the consistency of our temperature scale. The only exception is BD+10°2179, which is a metal-poor star according to Heber (1983) and therefore has less line blocking in the SWP-region. Since line blocking in LWR is unimportant at 18,000 K, the net effect is a larger R value compared to stars with normal metallicity.

We have also plotted BD+13^{o}3224 for comparison. In this case the error bars indicate the range of R and T_{eff} due to their variation over a pulsational cycle (P = 0.1078 d, Hill et al., 1981). The UV flux is variable with the same period, and a detailed investigation will be published elsewhere (Lynas-Gray et al., 1983). Two hydrogen deficient binaries, υ Sgr and KS Per, are also shown in Fig. 2, and the pertinent data is included in Table 2. The effective temperatures were estimated by comparing the (dereddened) flux distributions longward of 2000 Å with those of single helium stars. They are located above our empirical R,T_{eff} relation because their hot companions are responsible for a flux excess shortward of 1600 Å. For a recent discussion of these binaries see Schönberner and Drilling (1983a) and Drilling and Schönberner (1982).

In the following, we shall comment on some of the objects listed in Table 2.

HD 160641:

This is the hottest star in our ensemble. It pulsates with a period of about 0.6 d or 0.7d with a total amplitude of $\Delta V \approx 0.1$ mag. (Landolt, 1975; Walker and Kilkenny, 1980). We do not know, however, the exact phase of our IUE observations because the period is poorly known. Our temperature is in remarkable agreement with that found by Aller (1954): 31,500 K. Fig. 3 compares our IUE-observations with the 32,500 K model.

BD -9^{o}4395:

Kaufmann and Schönberner (1977) found T_{eff} = (25,000 ± 1,500) K by the fine analysis of visual spectrograms using a grid of unblanketed model atmospheres. Taking into account the differences between the old grid and the one used here, the agreement between the two independent temperature

determinations is excellent. A comparison between observed and predicted fluxes can be found in Heber and Schönberner (1980).

BD +10^{o}2179:

This star has recently been fine analyzed by Heber (1983), using the same grid of model atmospheres, and the result is T_{eff} = (16,800 ± 600) K. We needed a 18,000 K model to match the observed flux distribution, in satisfactory agreement with the fine analysis. In passing we note that BD +10^{o}2179 is suspected to pulsate with a period of about 4 h (Bartolini _et al._, 1982).

HD 124448:

The fine analysis of Schönberner and Wolf (1974) yielded T_{eff} = (16,000 ± 800) K, and again we have excellent agreement with the result presented in this paper. A comparison between observed and theoretical fluxes has already been given elsewhere (Schönberner _et al._, 1982).

MV Sgr:

This is a very interesting object because it is supposed to be a hot R CrB-star. Unfortunately, the existing low resolution IUE images are not of sufficient quality to tell us anything about mass loss (Rao and Nandy, 1982). We derived a lower value for the color excess than these authors, namely 0.38 mag as compared to 0.55 mag, and consequently we found a lower effective temperature, 15,500 K as compared to 18,000 K. We think the lower value is correct, because we got a clear reversal of the 2200 Å bump when we

applied E(B-V) = 0.55 mag. We show MV Sgr compared to a 16,000 K model in Fig. 4. Here, we have used the UBV photometry of Glass (1978) and the infrared photometry of Feast and Glass (1973). The model fits perfectly, and indeed the spectral appearance of MV Sgr in the UV resembles HD 124448. The only exceptions are the carbon lines, which appear weaker in MV Sgr.

The similarity of MV Sgr to HD 124448 also implies a similar evolutionary stage. The light-to-mass ratio for HD124448 is about 10^4 according to Schönberner and Wolf (1974) and we can assume the same for MV Sgr. With a reasonable mass of ~ 1 $M_{\odot}$, both stars would then have ~ 10^4 $L_{\odot}$, the only difference being the absence of gas and dust around HD 124448.

Finally, let us comment on the binary model for MV Sgr, which was proposed by Rao and Nandy (1982). In this model, the circumstellar gas and dust is provided by a cool supergiant which, however, has to be completely obscured by the very same dust. This model is implausible for the following reasons: first, MV Sgr is itself a giant (see above), and second, the existence of hydrogen-deficient binaries can only be understood if the helium star is the more evolved but (now) less massive star which is losing mass for a second time (Schönberner and Drilling, 1983a). If MV Sgr has a companion, it is certainly not a cool supergiant. To settle the important question of whether or not MV Sgr is a binary, we urgently need radial velocity measurements.

LSII +33°5:

Colors and spectral appearance (at low dispersion) suggest an effective temperature above 20,000 K (Drilling, 1978; Heber and Schönberner, 1981). The UV flux, however, is incompatible with such a high temperature and indicates a temperature even lower than that of HD 124448 (see Fig. 1). We found small differences between our two sets of IUE observations, quoted as cases A and B

in Table 2, and it cannot be ruled out that this star is variable. Fig. 5 shows the 'A' images together with a 15,000 K model.

LSE 78:

This star resembles LSII +33^{o}5 in all respects: spectral appearance and colors are in contrast to the UV flux which indicates a much lower temperature (Fig. 1). Fine analyses for both objects are needed to resolve this discrepancy.

HD 168476:

The fine analysis of Walker and Schönberner (1981) gives T_{eff} = (14,000 ± 500) K for this star. We needed a 13,000 K model to fit the continuum flux, still a satisfactory agreement, especially if one takes into account the differences between the two grids of model atmospheres (Fig. 6).

BD -1^{o}3438:

The preliminary result of a fine analysis is T_{eff} = (12,500 ± 1,000) K (Schönberner 1978), which again matches well with the 12,000 K model we needed for fitting the continuous flux.

BD +1^{o}4381:

This is the only cool extreme helium star bright enough to get well exposed images in both IUE cameras. A fine analysis is not yet available. Fig. 7 shows the observations compared with a 10,000 K model.

V. DISCUSSION

We have established an effective temperature scale for all known extreme helium stars by combining spacecraft and ground-based observations. The temperatures range from 8,500 to 32,000 K. The temperatures derived from the Stefan-Boltzmann law agree remarkably well with those based on ionization equilibria (i.e., with the results of fine analyses). The present work confirms the results of Heber and Schönberner (1981), but some differences must be noted. First, below ~ 14,000 K our temperatures are systematically lower than those of Heber and Schönberner, most likely because these authors did not consider the blocking effect of numerous lines besides He I in their computation of colors. Second, for two objects, LSII +33°5 and LSE 78, effective temperatures derived from the colors disagree with those derived from the Stefan-Boltzmann law. We have to admit, however, that according to Heber and Schönberner (1981), the Johnson photometry is not very sensitive to the temperatures of B-type helium stars, and that small photometric errors can cause significant temperature changes. The temperature difference between 15,000 and 20,000 K corresponds to only $\Delta(U-B) \approx 0.12$ mag. The situation is somewhat better for the Strömgren system: $\Delta(u-b) \approx 0.25$ mag for the same temperature interval. Thus the Strömgren system is to be preferred for photometric observations of helium stars.

It seems remarkable that 10 out of 13 extreme helium stars have effective temperatures below 16,000 K, or 7 out of 13 even below 14,000 K. We find only one cool object, LSIV -14°109 (T_{eff} = 8,500 K), which can provide us with an evolutionary link between the cool HdC or R CrB stars (T_{eff} < 7000 K) and the hotter helium stars. We believe, however, that our ensemble is far from being complete at cooler temperatures (see the discussion in Heber and

Schönberner, 1981). The number of hot helium stars (T_{eff} > 18,000 K, but < 40,000 K) is also very small: so far only two are known (BD $-9^{o}4395$ and HD 160641). More observational effort is needed to increase the number of known extreme helium stars.

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Table 1: Color excesses of extreme helium stars.

Star	Images	E_{B-V} This paper	E_{B-V} Heber and Schönberner
BD $+10^{o}2179$	LWR 4168 SWP 4825	0.0	0.0
HD 124448	LWR 3347 SWP 5790	0.08	0.04
LSS 3378	LWR 5052 SWP 5802	0.35	0.54
BD $-9^{o}4395$	LWR 5061 SWP 5812	0.30	0.31
LSE 78	LWR 8454 SWP 9713	0.10	--
HD 160641	LWR 8467 SWP 9741	0.40	--
LSIV $-1^{o}2$	LWR 8455 LWR 11393 SWP 9714 SWP 14796	0.45	0.52
BD $-1^{o}3438$	LWR 13319 SWP 17049	0.40	0.55
HD 168476	LWR 7247 SPW 8300	0.12	0.13
MV Sgr	LWR 6053 SWP 7120	0.38	0.45
LSIV $-14^{o}109$	LWR 8466 LWR 13322 SWP 17052	0.20	0.43
LSII $+33^{o}5$	LWR 5035 (A) SWP 5743	0.22	0.37
LSII $+33^{o}5$	LWR 11418 (B) SWP 14820	0.23	
BD $+1^{o}4381$	LWR 5037 SWP 5795	0.10	0.23

Table 2. Angular diameters and effective temperatures of extreme helium stars

Star	T_{eff}(model)	$\Theta^2 \times 10^{21}$	T_{eff}	R
BD +10°2179	18,000	1.80	17,700 ± 600	1.30
HD 124448	16,000	2.74	15,500 ± 500	0.93
LSS 3378	10,000	4.54	9,400 ± 500	0.18
BD-9°4395	24,000	1.62	23,000 ± 700	1.22
LSE 78	14,000	1.13	13,600 ± 400	0.60
HD 160641	32,500	2.98	31,900 ± 1,500	1.51
LSIV-1°2	12,500	5.04	11,900 ± 400	0.43
BD-1°3439	12,000	8.35	10,900 ± 600	0.22
HD 168476	13,000	9.25	12,400 ± 400	0.50
MV Sgr	16,000	0.38	15,400 ± 500	0.93
LSIV-14°109	9,000	5.62	8,400 ± 500	0.14
LSII +33°5(A)	15,500	3.24	15,000 ± 500	0.71
LSII +33°5(B)	15,000	3.32	14,500 ± 500	0.64
BD +1°4381	10,000	12.6	9,500 ± 400	0.20
υ Sgr 1)	10,500	---	---	0.65
KS Per 2)	9,000	---	---	0.75
BD +13°3224 3)	28,000	0.8	26,500	1.4

1) E_{B-V} = 0.12.

2) E_{B-V} = 0.35.

3) E_{B-V} = 0.07, SWP and LWR not at same phase!

FIGURE CAPTIONS

Fig. 1: IUE spectrograms of extreme helium stars arranged in the order of decreasing temperature. In part b, all spectrograms are two times larger than in part a. We have plotted LSE 78 in both parts in order to emphasize the difference in scale.

Fig. 2: Empirical relation R vs. T_{eff} for extremely helium-rich single stars. The dashed curve is a best fit by eye through the data points. Helium rich binaries are also plotted (open circles).

Fig. 3: Dereddened flux distribution of HD 160641 compared with a 32,500 K, log g = 3.5 model atmosphere.

Fig. 4: Dereddened flux distribution of MV Sgr compared with a 16,000 K, log g = 2 model. Below is shown the result if a color excess of 0.55, rather than 0.38, is assumed.

Fig. 5: Dereddened flux distribution of BD $+33^{o}5$ (A) compared with a 15,000 K, log g = 2 model atmosphere.

Fig. 6: Dereddened flux distribution of HD 168476 and a 13,000 K, log g = 1.5 model atmosphere.

Fig. 7: Dereddened flux distribution of BD $+1^{o}4381$ and a 10,000 K, log g = 1 model atmosphere.

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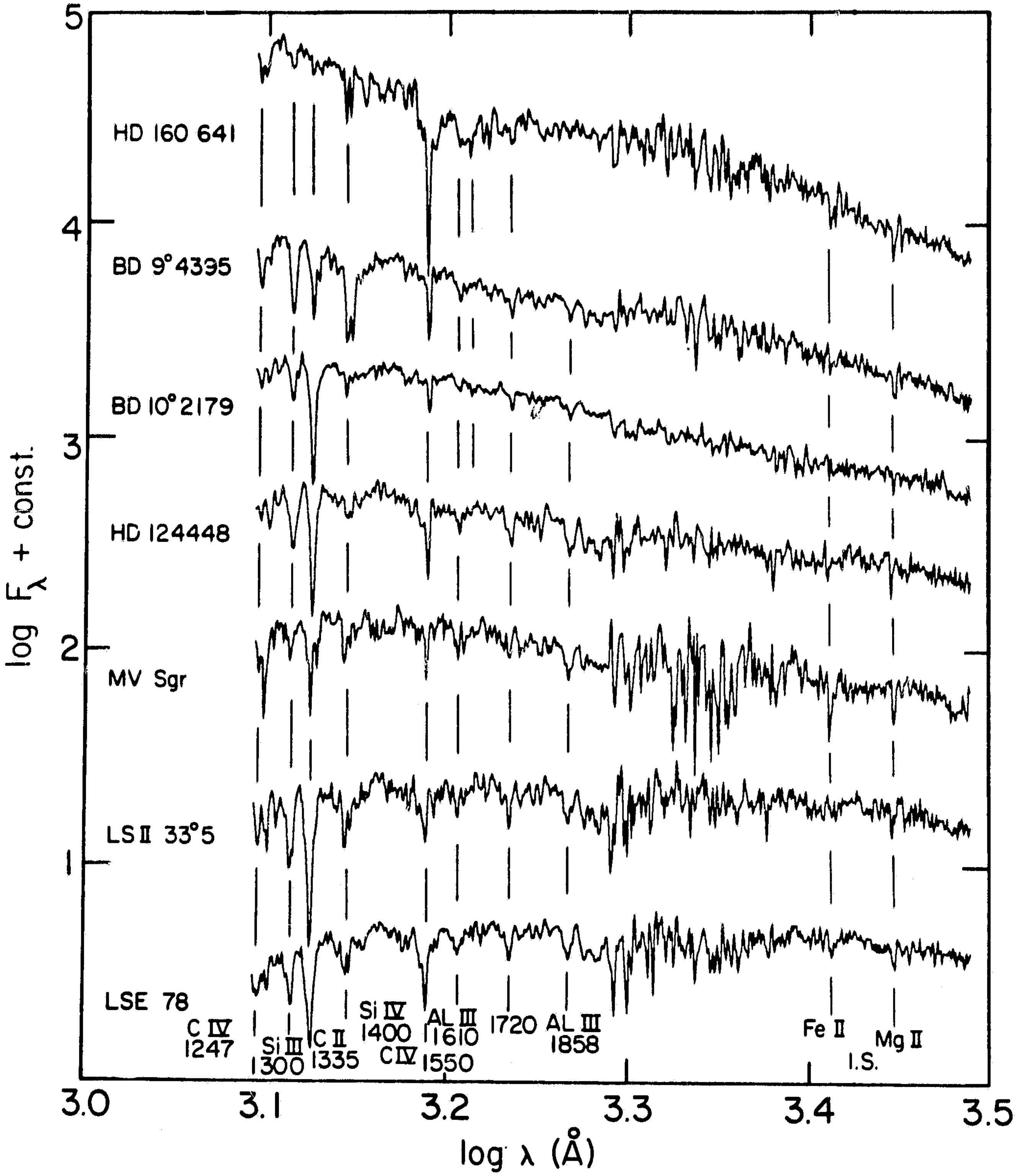

Fig. 1a - Drilling et al.

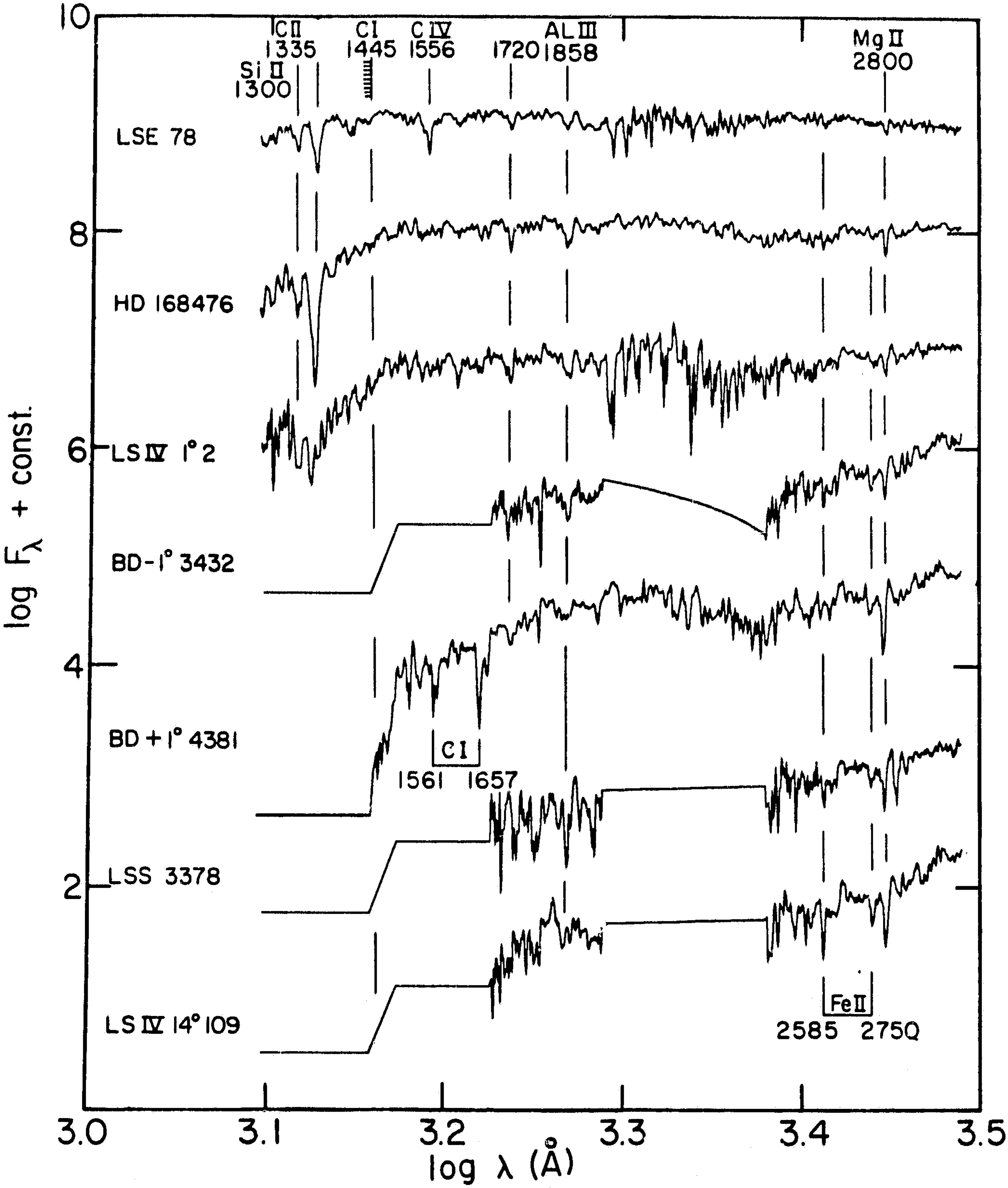

Fig. 1b - Drilling et al.

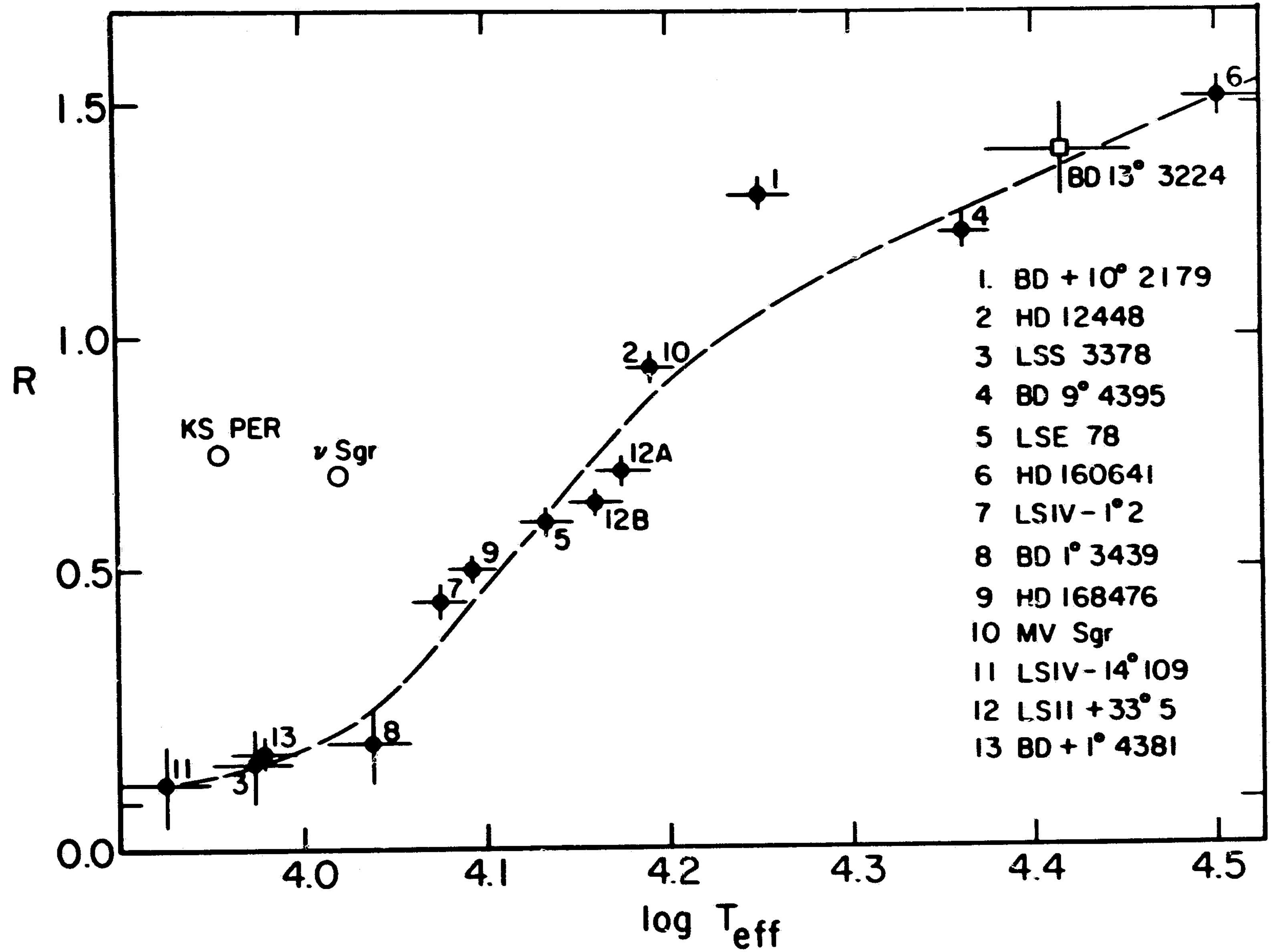

Fig. 2 - Drilling et al.

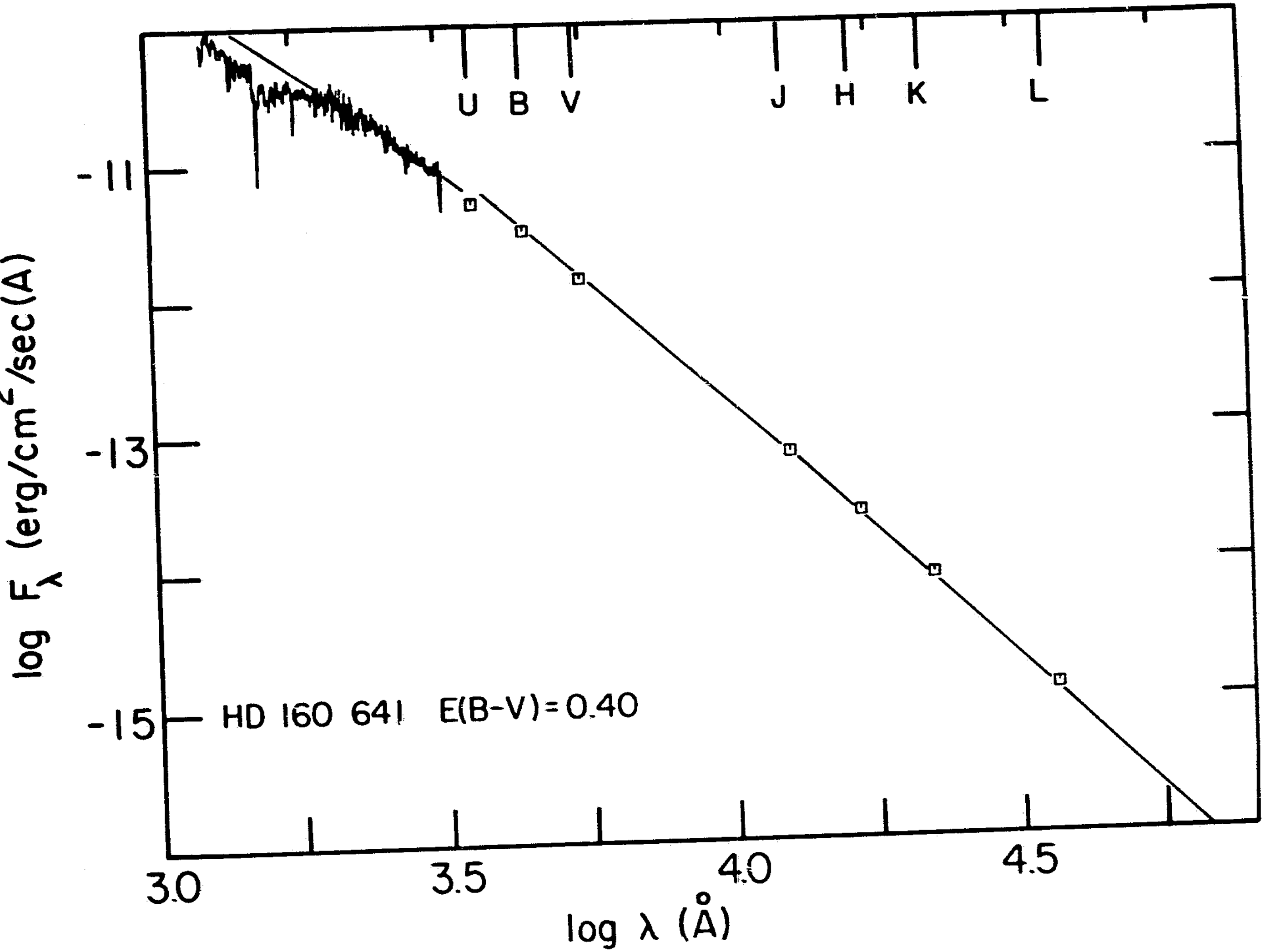

Fig. 3 - Drilling et al.

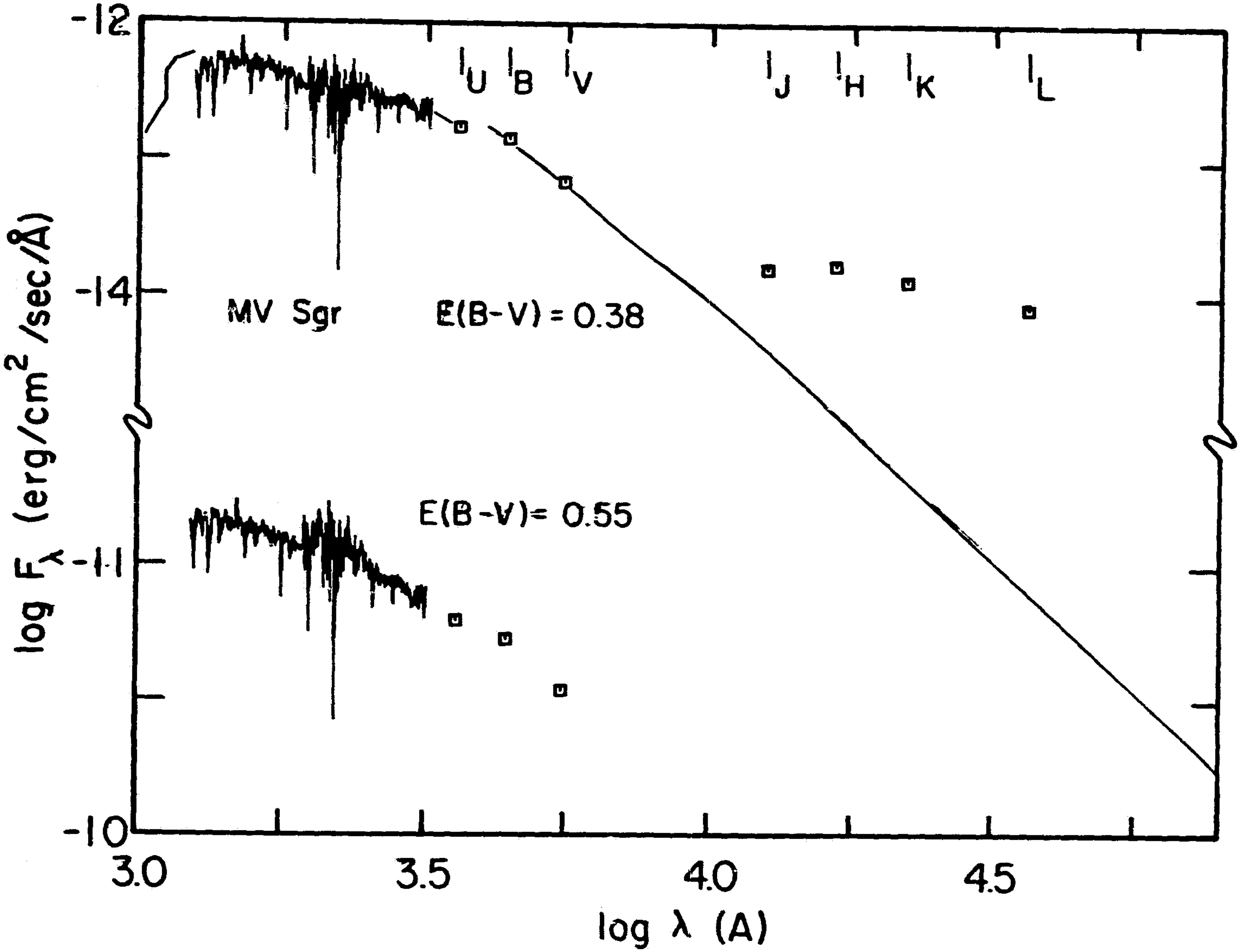

Fig. 4 – Drilling et al.

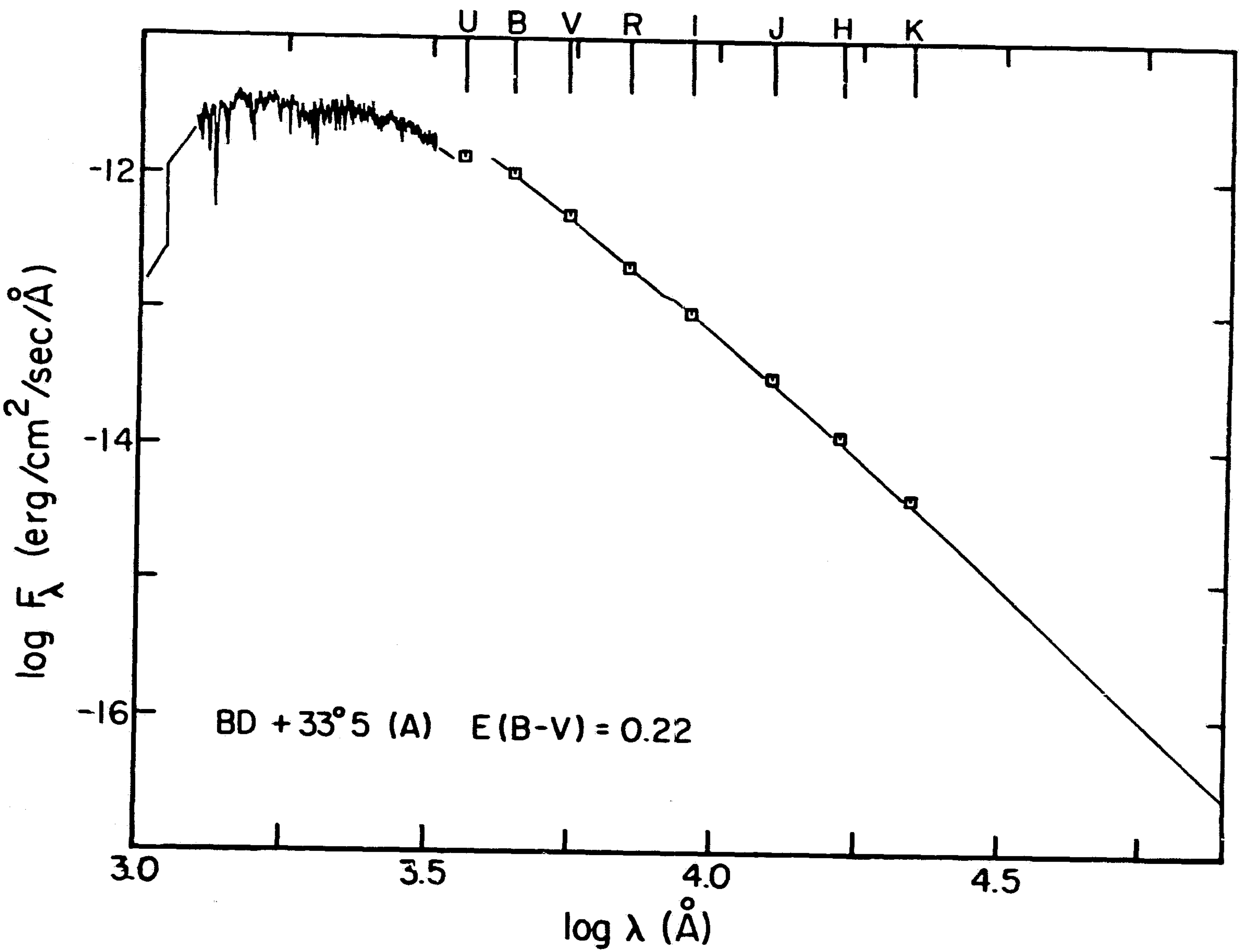

Fig. 5 - Drilling et al.

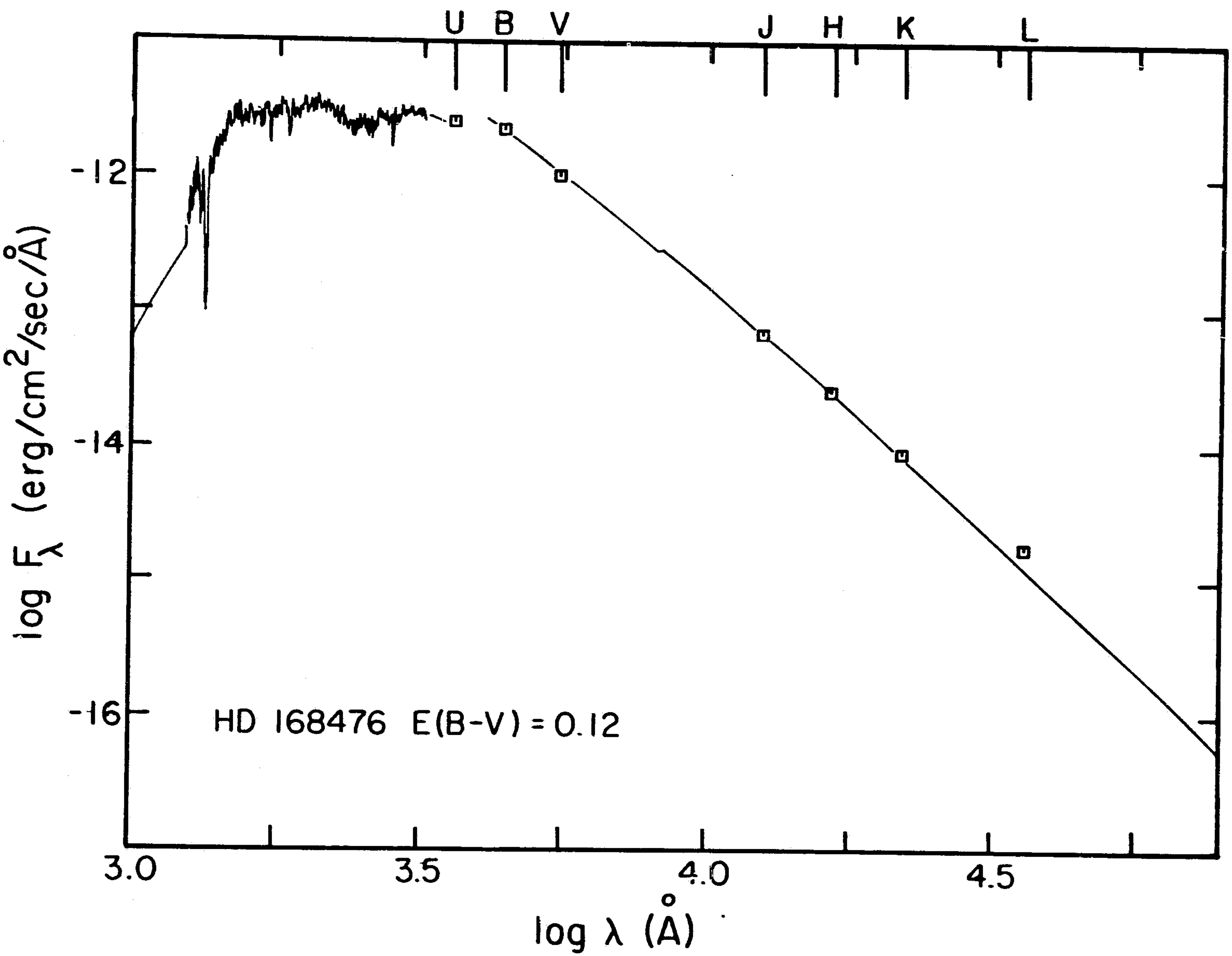

Fig. 6 - Drilling et al.

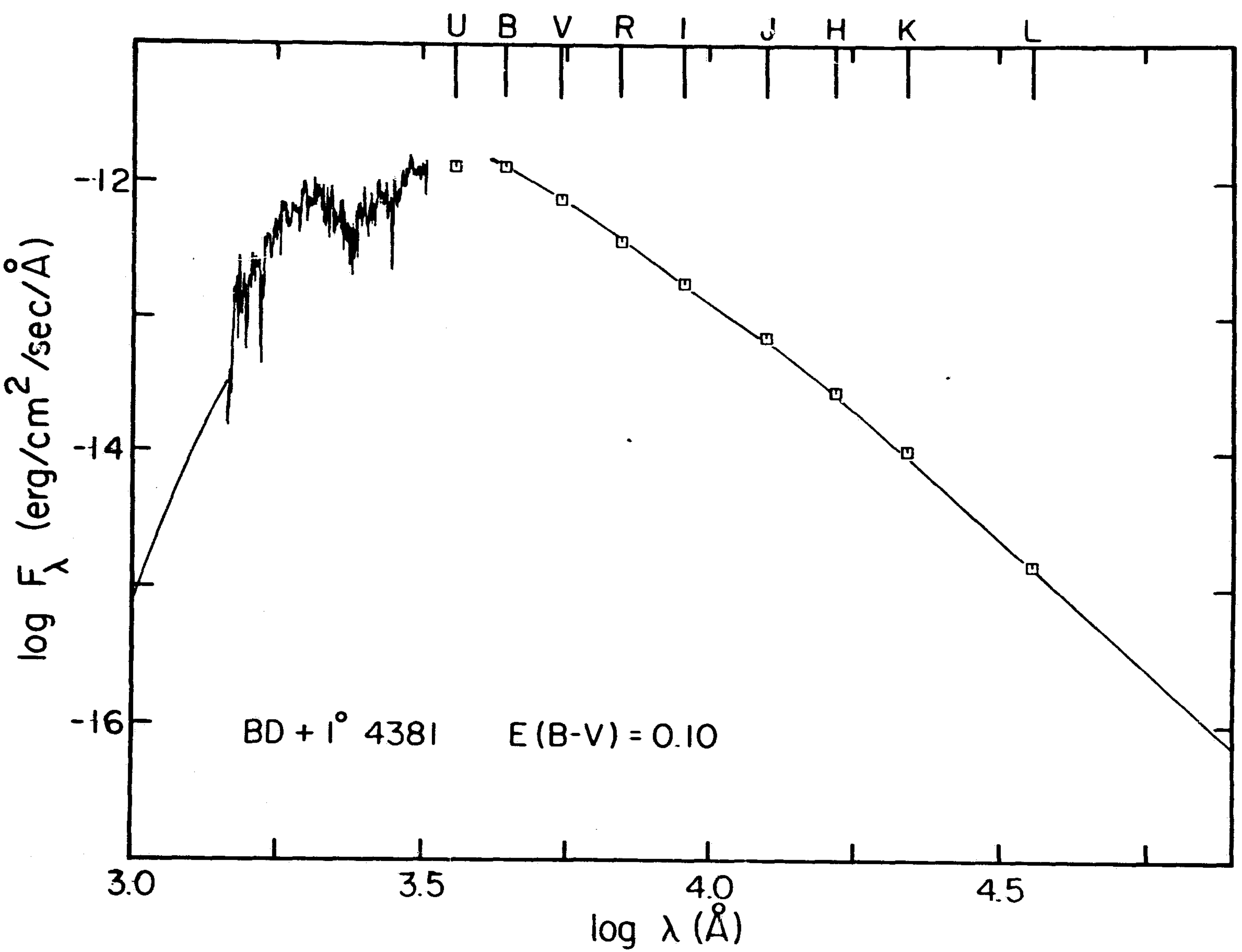

Fig. 7 - Drilling et al.